

Abstract

Radiant Cooling in US Office Buildings:
Towards Eliminating the Perception of Climate-Imposed Barriers

by

Corina Stetiu

Doctor of Philosophy in Energy and Resources

University of California at Berkeley

Professor Gene I. Rochlin, Chair

The intensive use of compressor-driven cooling in the developed countries has both direct and indirect negative effects on the environment that are realized on local and global scales. Predicted increases in the use of air-conditioning in the developing countries will magnify the range and scope of these effects. Much attention is therefore being given to improving the efficiency of air-conditioning systems through the promotion of more efficient cooling technologies.

One such alternative, radiant cooling, is the subject of this thesis. Performance information from Western European buildings equipped with radiant cooling systems indicates that these systems not only reduce the building energy consumption but also provide additional economic and comfort-related benefits. Their potential in other markets such as the US has been largely overlooked due to lack of practical demonstration, and to the absence of simulation tools capable of predicting system performance in different climates.

This thesis describes the development of RADCOOL, a simulation tool that models thermal and moisture-related effects in spaces equipped with radiant cooling systems. The thesis then conducts the first in-depth investigation of the climate-related aspects of the performance of radiant cooling systems in office buildings. The results of the investigation show that a building equipped with a radiant cooling system can be operated in any US climate with small risk of condensation. For the office space examined in the thesis, employing a radiant cooling system instead of a traditional all-air system can save on average 30% of the energy consumption and 27% of the peak power demand due to space conditioning. The savings potential is climate-dependent, and is larger in retrofitted buildings than in new construction.

This thesis demonstrates the high performance potential of radiant cooling systems across a broad range of US climates. It further discusses the economics governing the US air-conditioning market and identifies the type of policy interventions and other measures that could encourage the adoption of radiant cooling in this market.

For Carole

TABLE OF CONTENTS

ABSTRACT	i
TABLE OF CONTENTS	iii
LIST OF FIGURES	x
LIST OF TABLES	xiv
ACKNOWLEDGMENTS	xvii
1. INTRODUCTION	1
1.1 Background	1
1.1.1 Motivation for this research	3
1.1.2 Thesis objectives	4
1.2 Thesis Outline	5
1.3 References	6
2. PRESENT STATE OF KNOWLEDGE ABOUT RADIANT COOLING SYSTEMS	8
2.1 All-Air Systems vs. Radiant Cooling Systems	8
2.2 Short History of Radiant Cooling Systems	9
2.3 Thermal Comfort Considerations	13
2.4 The Cooling Power of Radiant Cooling Systems	15
2.5 Numerical Modeling of Radiant Cooling Systems	18
2.6 Cooling Performance of Radiant Cooling Systems: Case Studies	18
2.7 Cooling Performance of Radiant Cooling Systems: Back-of-the-Envelope Calculation	20

2.8 Economics of Radiant Cooling Systems	22
2.9 Types of Radiant Cooling Systems	23
2.10 Radiant Cooling System Controls	28
2.11 Summary	29
2.12 References	29
 3. RADCOOL - A TOOL FOR MODELING BUILDINGS EQUIPPED WITH RADIANT COOLING SYSTEMS	 33
3.1 Modeling Approach	33
3.1.1 Model capabilities	34
3.1.2 Model limitations	34
3.2 Model Evaluation	35
3.2.1 Intermodel comparison with DOE-2	35
3.2.2 Comparison with measured data	41
3.3 Conclusions	49
3.4 Future work	49
3.5 References	51
 4. RADIANT COOLING IN US OFFICE BUILDINGS: DESIGN OF THE MODELING PROJECT	 53
4.1 Introduction	53
4.2 The Issue	53
4.3 The Parametric Study	54
4.4 Working with the RADCOOL-Imposed Constraints	56
4.4.1 The base-case building	56
4.4.2 The base-case space	60

4.4.3 The locations for the parametric study	67
4.4.4 The location-specific simulation periods	71
4.5 Comparing the Results of the RADCOOL and DOE-2 Simulations	79
4.5.1 Using the results of RADCOOL and DOE-2 to compare the energy consumption and peak power demand of the radiant cooling system and the all-air system	80
4.6 Capabilities and Limits of the Parametric Study	81
4.7 References	83
 5. RADIANT COOLING IN US OFFICE BUILDINGS: RESULTS OF THE MODELING PROJECT	 85
5.1 Chapter Outline	85
5.2 Indoor Conditions	86
5.3 The Energy Consumption and Peak Power Demand of the Radiant Cooling System	94
5.3.1 Energy consumption of the radiant cooling system	95
5.3.2 Peak power demand of the radiant cooling system	96
5.4 The Energy Consumption and Peak Power Demand of the All-Air System	97
5.4.1 Energy consumption of the all-air system	97
5.4.2 Peak power demand of the all-air system	99
5.5 Comparison of the Performance of the Radiant Cooling System and of the All-Air System	99
5.5.1 Energy consumption	99
5.5.2 Peak power demand	102
5.5.3 Climate-induced trends into the energy and peak power savings of the radiant cooling system	103
5.6 Additional Modeling	111

5.6.1 Description of the additional simulations	111
5.6.2 Results of the additional simulations	112
5.7 Conclusions	115
5.8 References	116
 6. RADIANT COOLING AND THE US MARKET	117
6.1 Introduction	117
6.2 The Economic Theory of Increasing Returns	117
6.3 The Regulatory Response	120
6.3.1 Theory	120
6.3.2 Application to cooling technologies	121
6.3.3 Other measures	123
6.4 Conclusion	127
6.5 References	127
 7. FUTURE RESEARCH DIRECTIONS	129
 Appendix A	
THE THERMAL BUILDING	
SIMULATION MODEL RADCOOL	132
A.1 SPARK as the Environment for RADCOOL	132
A.2 The Structure of RADCOOL	133
A.2.1 Preliminary data processing	134
A.2.2 Create the SPARK files describing the problem, run SPARK	134
A.2.3 Output data processing	134
A.3 The SPARK Building Component Library	134
A.4 The Passive Building Components	137

A.4.1 One-dimensional heat transfer	137
A.4.1.1 The one-dimensional heat conduction/storage equation	137
A.4.1.2 The RC approach to solve the heat conduction/storage equations for one solid layer in SPARK	139
A.4.2 The structure of the passive wall in SPARK	140
A.4.2.1 The equations for the temperature nodes in SPARK	141
A.4.2.2 Test to determine the accuracy of the RC model for one-dimensional heat transfer	142
A.4.3 Exterior surface radiant heat balance for a wall with thermal mass	144
A.4.3.1 The convective heat flux on the surface of a wall	145
A.4.3.2 The long wave (IR) heat flux exchange between a wall and its exterior surroundings	146
A.4.3.3 The solar radiation incident on the surface of a wall	148
A.4.4 Interior surface radiant heat balance for a wall with thermal mass	149
A.4.4.1 The convective heat flux on the interior surface of a wall	150
A.4.4.2 The long wave radiative exchange between a wall and the other room surfaces	151
A.4.4.3 Solar and internal radiation incident on the interior surface of a wall	153
A.4.5 The four-layer passive floor with thermal mass	154
A.4.5.1 Comparison between the floor and the wall with thermal mass	154
A.4.5.2 The exterior surface radiant heat balance for a passive floor with thermal mass	155
A.4.6 The two-pane window with thermal mass	156

A.4.6.1 Comparison between a two-pane window and a multi-layer wall	156
A.4.6.2 Heat conduction/storage for a two-pane window	156
A.4.6.3 The heat balance for the exterior pane of a two-pane window	158
A.4.6.4 The heat balance for the interior pane of a two-pane window	158
A.5 The Active Building Components	159
A.5.1 Two-dimensional heat transfer analysis	159
A.5.1.1 The two-dimensional heat conduction/storage equations	160
A.5.1.2 The RC solution to the two-dimensional heat conduction/storage equations	160
A.5.1.3 The two-dimensional model of the ceiling in SPARK	161
A.5.1.4 Test to determine the accuracy of the RC model for two-dimensional heat transfer	165
A.5.2 The two-dimensional SPARK model of the core-cooling ceiling	166
A.5.2.1 Heat transfer between the pipe and the water when the water is flowing	167
A.5.2.2 Heat transfer between the pipe and the water when the water is recirculated	168
A.5.2.3 Heat transfer between the pipe and the water when the water is stagnant	170
A.5.2.4 The two-dimensional model of a cooled ceiling	171
A.5.3 The cooling panel	173
A.5.3.1 The model of the cooling panel	173
A.6 Types of Radiant Cooling System Controls	176
A.6.1 The thermostat-based control	176

LIST OF FIGURES

Chapter 2

2.1. Air flow and heat exchange in a room with cooled ceiling.	12
2.2. Construction of a cooling panel.	24
2.3. Heat transfer for the panel system (cooling mode).	25
2.4. Construction of a cooling grid.	26
2.5. Heat transfer for ceiling with cooling grid.	26
2.6. Heat transfer for concrete core cooling system.	27

Chapter 3

3.1 Single-zone structure simulated for the intermodel comparison.	36
3.2 The three wall assemblies simulated for the intermodel comparison.	38
3.3 Outside and indoor air temperature: wall assembly 1 (concrete).	40
3.4 Outside and indoor air temperature: wall assembly 2 (typical construction).	40
3.5 Outside and indoor air temperature: wall assembly 3 (wood).	41
3.6 The DOW Chemicals test room orientation and layout.	42
3.7 Composition of the vertical walls in the DOW Chemicals test room.	43
3.8 Composition of the roof and floor in the DOW Chemicals test room.	43
3.9 Air temperature inside the DOW Chemicals test room.	48

Chapter 4

4.1 Base-case building orientation and layout.	58
4.2 Base-case building construction for the parametric study.	59
4.3 Space contributions to the building energy consumption. Statistic performed for 11 building locations.	63

4.4 Estimate of building energy consumption from space energy consumption.	64
4.5 Ventilation strategies: schedules for weekday hours.	66
4.6 Climate classification based on the dehumidification energy and total energy necessary to condition the ventilation air.	69
4.7 US commercial buildings - classification by principal activity.	72

Chapter 5

5.1 Indoor air temperature comparison at the New Orleans location during the week of system peak. Space ventilated continuously, half rate at night.	87
5.2 Indoor air temperature comparison at the New Orleans location during the day of system peak. Space ventilated continuously, half rate at night.	87
5.2 Indoor air relative humidity comparison at the New Orleans location during the week of system peak. Space ventilated continuously, half rate at night.	88
5.4 Comparison of cooling panel surface temperature and dew-point temperature. New Orleans, space ventilated continuously, half rate at night	88
5.5 Indoor air temperature comparison at the New Orleans location during the week of system peak. Space ventilation interrupted at night.	89
5.6 Indoor air temperature comparison at the New Orleans location during the day of system peak. Space ventilation interrupted at night.	89
5.7 Indoor air relative humidity comparison at the New Orleans location during the week of system peak. Space ventilation interrupted at night.	90
5.8 Comparison of cooling panel surface temperature and dew-point temperature. New Orleans, space ventilation interrupted at night.	90

5.9 Distribution of the energy and peak power savings of the radiant cooling system with the number of locations. Space ventilation interrupted at night.	104
5.10 Energy savings over the cooling season: trend across climates.	106
5.11 Fractional energy savings over the cooling season: trend across climates.	107
5.12 Peak power savings: trend across climates.	108
5.13 Fractional peak power savings: trend across climates.	109
5.14 Distribution of the energy and peak power savings of the radiant cooling system with the number of locations.	110
5.15 Energy savings over the cooling season: data for New Orleans and Phoenix.	113
5.16 Peak power savings: data for New Orleans and Phoenix.	114

Appendix A

A.1 RADCOOL program flow.	133
A.2 Volume element for conduction heat flow.	137
A.3 A wall layer with three sub-layers.	140
A.4 A wall layer with four sub-layers.	141
A.5 The RC model of the 4-layer wall.	141
A.6 Temperature at the midpoint of a homogeneous wall: comparison between the one-dimensional SPARK model and the analytical solution.	144
A.7 The heat flux balance at the exterior surface node.	145
A.8 The long wave radiation exchange at the exterior surface of a wall.	146
A.9 The heat flux balance at the interior surface temperature node.	149
A.10 Different gradients for air and room temperatures.	150
A.11 The RC circuit of a two-pane window.	156
A.12 A 3x5 grid. RC equivalent circuit for heat transfer calculations.	162

A.13 A 5x5 grid. RC equivalent circuit for heat transfer calculations.	163
A.14 Temperature at the midpoint of a homogeneous ceiling: comparison between the 3x5 grid SPARK model and the analytical solution.	165
A.15 Temperature at the midpoint of a homogeneous ceiling: comparison between the 5x5 grid SPARK model and the analytical solution.	166
A.16 Structure of a cooled ceiling with imbedded pipes.	166
A.17 Equivalent RC circuit for heat transfer calculation in the case of a cooled ceiling.	172
A.18 Layout of a cooling panel system.	174
A.19 The heat balance in the case of the cooling panel.	175
A.20 Thermostat-based control strategy.	177
A.21 Timer-based control strategy.	177
A.22 Hybrid control.	178
A.23 Air temperature nodes in a room modeled by RADCOOL.	180
A.24 Heat balance for the room air.	182
A.25 Heat balance for the plenum air.	188
A.26 Relative positions of two rectangular surfaces that give exact solutions for the shape factors.	203
A.27 Radiation exchange between finite areas with one area subdivided.	205

LIST OF TABLES

Chapter 2

2.1 Data about the radiant cooling systems installed in Germany in 1994.	13
2.2 Assumptions used for the comparison of peak power requirements for an all-air system and a RC system conditioning the same office space.	21
2.3 Estimated electrical power demand for the removal of internal loads from a two-person office with a floor area of 25 m ² .	22
2.4 Estimated annual energy consumption [kWh/m ²] for a European office building with a floor area of 5000 m ² .	23
2.5 Estimated space requirements for air-conditioning systems in a European office building with a floor area of 5000 m ² .	23

Chapter 3

3.1 Material properties used in the intermodel comparison.	37
3.2 Summary of assumptions for the intermodel comparison.	39
3.3 Material properties used in the comparison with measured data.	44
3.4 Summary of assumptions for the comparison with measured data.	47

Chapter 4

4.1 Material properties simulated in the parametric study.	57
4.2 Energy consumption for cooling and dehumidification of ventilation air. Climate classification and locations selected for the study.	70
4.3 Office buildings in the largest metropolitan areas and their distribution with respect of the climate classification.	71
4.4 Summary of assumptions for the parametric study.	77

Appendix A

A.1 Material-specific coefficients occurring in equation (A.136).	193
A.2 Material-specific coefficients occurring in equation (A.145).	195
A.3 Permeability, diffusion coefficient, and effective penetration depth of different materials.	196
A.4 Coefficients for equation (A.150).	200
A.5 Coefficients for equation (A.160).	202

Appendix B

B.1 Energy consumption and peak power demand in New Orleans. SW orientation, new building construction.	209
B.2 Energy consumption and peak power demand in Cape Hatteras. SW orientation, new building construction.	210
B.3 Energy consumption and peak power demand in New York City. SW orientation, new building construction.	211
B.4 Energy consumption and peak power demand in Fort Worth. SW orientation, new building construction.	212
B.5 Energy consumption and peak power demand in Chicago. SW orientation, new building construction.	213
B.6 Energy consumption and peak power demand in Boston. SW orientation, new building construction.	214
B.7 Energy consumption and peak power demand in San Jose, CA. SW orientation, new building construction.	215
B.8 Energy consumption and peak power demand in Phoenix. SW orientation, new building construction.	216
B.9 Energy consumption and peak power demand in Scottsbluff. SW orientation, new building construction.	217

B.10 Energy consumption and peak power demand in Salt Lake City.	
SW orientation, new building construction.	218
B.11 Energy consumption and peak power demand in Seattle.	
SW orientation, new building construction.	219
B.12 Energy consumption and peak power demand in New Orleans.	
NE orientation, new building construction.	220
B.13 Energy consumption and peak power demand in Phoenix.	
NE orientation, new building construction.	221
B.14 Energy consumption and peak power demand in New Orleans.	
SW orientation, old building construction.	222
B.15 Energy consumption and peak power demand in Phoenix.	
SW orientation, old building construction.	223

ACKNOWLEDGMENTS

First and foremost, I must thank my advisers Gene Rochlin and Helmut Feustel, without whose help this thesis would have never come into existence.

However busy, Gene always found time to meet with me, listen to my concerns, and help me get un-stuck. A true ERGie himself, Gene encouraged me time and again to look at everything in context, and taught me to be self-conscious while doing research. Some of my best memories of graduate school are those of sharing laughter and brownies with Gene while discussing my work. Thank you.

Helmut dedicated many hours and lots of energy to help me formulate a thesis topic that was interesting and challenging for both of us. By constantly questioning the direction of my research and the validity of my results, Helmut taught me to defend my point of view, and helped me remain focused. He also ensured my financial support all the way through graduate school, so I can avoid going in debt before graduation. Thank you.

I must also thank Bill Nazaroff and Cris Benton. They were always available to discuss my progress, and offered invaluable suggestions at various stages of my work. I thank them for their time, help and encouragements. Without their advice my struggles would have been significantly more painful, and this dissertation much harder to “digest”.

I am grateful to *Meierhans & Partner, AG* for their financial support during my first year as a graduate student, and for sharing their field measurements with me. I thank the California Institute for Energy Efficiency for funding the development of RADCOOL through an “exploratory project”. I thank Richard H. Karney for the financial support that I received through the years from the US Department of Energy, and for his constant interest in my work.

Carrying out the computer work that constitutes the core of this thesis would have been impossible without the help of the Simulation Research Group at the LBNL. Fred Winkelmann, Fred Buhl, Ender Erdem and Kathy Ellington showed me the tricks behind the magic of building simulations, and provided guidance in my early work with SPARK. Thank you.

Two other colleagues at LBNL have constantly helped me through the years. Brian Smith made sure that my computer was always ready for data-crunching, and designed many of the figures in the thesis. Rick Diamond good-naturedly answered all my questions, offered useful inputs and comments, and cheered me up when times were rough. Thank you both.

The friendships with which I have been blessed at Berkeley have helped me overcome the initial (and later) difficulties associated with studying in the US. Many thanks go to my dear friends Libby Schnieders, Katy Janda, Alison Kwok, JoAnn Ten Brinke, Karin Hansen, Elana Swartzman and Scott Benson, and to my roommates Marc Melcher, Jack Dennerlein, Chris Pawlowski, Shirley Yang and Hana Filip.

For their unconditional love, I am eternally grateful to my family. Without the encouragement and support that they have constantly offered me, I would have never launched into this great adventure of becoming... a doctor!

Finally, I thank my best friend and husband, David Jump, for having always been there for me. David has stood by me at times of disappointment, and has shared my joy for every success, however minor. He has supported my decisions, and has shown me how to have fun throughout it all. Through his personal and professional achievements, he has been a constant source of inspiration. Thank you with all my heart.